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Damage caused by an exceptionally warm and dry early summer on newly planted Norway spruce container seedlings in Nordic boreal forests

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ABSTRACT

With climate change, drought and warm growth conditions in the spring and early summer are predicted to become more common in Nordic boreal zones in the future. Such conditions occurred in Finland in June and July 2021, offering a good opportunity to study the field performance of seedlings and which factors, including the weather, regeneration site, and operational or seedling level factors, affected the field performance of the seedlings. In the survey, 65 regeneration sites planted with Norway spruce (*Picea abies* (L.) Karst.) container seedlings from May to July 2021 were randomly selected from different parts of South and Central Finland (60–64°N), and several variables were assessed in sample plots from these sites in September–October 2021. On average, 6 % of the seedlings died, and 26 % were damaged during the first growing season. In most cases, the damage was caused by drought. The most important factors affecting drought risk were the planting period and packaging and storage methods of the seedlings: in freezer-stored seedlings, the probability of drought damage was <0.20 for all planting periods, except for July; when the seedlings overwintered outdoors and were delivered to the forest in open trays, the risk of damage was <0.25 when they had been planted in May and early June, but in late June, it was > 0.60. When the seedlings had overwintered outdoors and were then packed in closed packaging, the risk was >0.20, regardless of the planting period. A low previous-year height of the seedlings (especially in the outdoor stored seedlings), precipitation a week before planting, and a low average temperature two weeks after planting reduced the risk of drought damage. When the average air temperature was below 15 °C (i.e., during the May plantings), the shade of the nearby stand slightly reduced the drought risk, but in higher temperatures, shade did not affect it. The effect of the pre-planting precipitation was stronger in coarse-textured and peat soils than in medium-coarse soils. The risk of drought damage was lowest when the freezer-stored seedlings were planted in good quality mineral soil mounds, deep enough in medium-rich (MT type) and medium-coarse soils. It is impossible to completely prevent drought damage in newly planted Norway spruce seedlings, but by optimizing operational choices and measures, the development of full density fast-growing young Norway spruce forests can also be ensured in a warming climate.

1. Introduction

Due to the warming climate, it has been predicted that spring and early summer drought periods will become more common in the Nordic boreal zone (Ruosteenoja et al. 2018), increasing the risk of drought damage to newly planted seedlings. In an inventory study in privately owned forests in southern Sweden, the differences in the available water between years and sites explained seedling survival rates three years after planting (Holmström et al. 2019). In Finland, an exceptionally warm and dry period occurred in the summer of 2021, when the daily mean temperature was above 25 °C for over three weeks (Finnish Meteorological Institute). A heat period lasting over two weeks occurs every tenth year and longer ones even less frequent in Finland (Finnish Meteorological Institute). The warm period offered a good opportunity to study the effects of warm and dry period on the field performance of newly planted seedlings in Nordic boreal conditions. In northern European forests, the Norway spruce (*Picea abies* (L.) Karst.) is a commercially important and widely planted tree species. However, of commercially important tree species, it is also the most sensitive to drought (Jansons et al. 2016), and its performance may suffer in

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Finland's future warming climate (Kellomäki et al. 2018). It is therefore important to know how newly planted Norway spruce seedlings survive during early season drought periods, and if any factors can be changed at an operational level along the planting chain to avoid drought damage.

Optimal air temperature for the shoot growth of Norway spruce seedlings is 18–24 °C (Heide 1974) and for net photosynthesis between 10 and 20 °C (Grossnickle 2000 and reference therein). In open regeneration sites, the soil surface temperatures may exceed 50 °C in northern latitudes, which may cause damage to conifer seedlings (Grossnickle 2000). During long-lasting heat period, the risk for high temperatures around the planted seedlings further increases. High air and soil temperatures also increase soil respiration as well as shoot and root respiration of Norway spruce seedlings (Pumpanen et al. 2012). Increasing respiration rate increases the risk of drought damage, especially if rainless period with high temperatures lasts for several weeks.

The availability of water and growth just after planting is essential for the successful establishment and further development of newly planted seedlings (Burdett 1990). Under drought stress, water uptake may be retarded, slowing the growth of seedlings. To avoid water stress in seedlings, continuous movement of water from roots to needles is needed to maintain water balance (Grossnickle 2000). Several seedling and regeneration site factors affect seedlings' water uptake and water balance. Available soil water, root system size and distribution, root-soil contact, and root hydraulic conductivity all affect the uptake of water (Grossnickle 2005). Differences in soil properties also affect seedlings' drought susceptibility (Rehschuh et al. 2017).

There is a complexity of factors affecting the field performance of newly planted seedlings (Grossnickle 2000) and their effects on the field performance of seedlings is often difficult. Seedling size, nursery growing history and seedlot affect the field performance of seedlings (Chen and Nelson 2020). Based on surveys of the field performance of conifer seedlings after severe winter conditions (Luoranen et al. 2018, 2022a) and machine plantings (Luoranen et al. 2011), we know that good mechanical site preparation (MSP) and planting improve seedlings' performance. Other operational conditions such as the duration of the field storage or packaging methods may increase the risk of failure (Luoranen et al. 2019, 2022a), as well as the lack of watering of seedlings during field storage before planting (Helenius et al. 2005a). These factors, alone or combined with dry and warm weather, may cause drought-like damage on seedlings and further reduce seedlings' field performance. Drought may also increase the risk of other damage. For example, pine weevil feeding damage is known to increase if seedlings suffer from drought (Selander and Immonen 1992).

Site conditions can affect the water conditions and water stress of planted seedlings. For example, the position of a seedling on a slope and the slope direction may affect soil water conditions and the risk of drought (Griffiths et al. 2009). In addition, soil water relations and, e.g., soil water potential, which is an important indicator of drought, vary in different soil texture types and are affected by the proportion of organic matter in soil (Saxton and Rowls 2006). Some microsite factors such as the presence of piles of logging residues, stumps, or vegetation near a planted seedling may also affect the water conditions (Harrington et al. 2013) and seedlings' survival by offering shade for the seedling (Devine and Harrington 2007; Reely and Nelson 2021).

Pine weevil (*Hylobius abietis* L.) is one of the most damaging agents in newly planted conifer seedlings in European forests (Långström and Day 2004; Lalík et al. 2021). The abundance of pine weevils and their feeding damage increase with increasing temperature sums (Nordlander et al. 2017), even if the changes in temperature sums are small between years and site in small geographical areas (Luoranen et al. 2022b). In an old study by Långström (1982), the abundance of pine weevils decreased from southern to northern Finland. Since that study, regeneration methods and seedling types have changed, and growing seasons have lengthened (temperatures sums increased). When the aim of drought damage inventory was to obtain the greatest possible geographical variation from southern to northern Finland, the data also offered a good opportunity to investigate variation in pine weevil feeding damage.

The study aimed to investigate the field performanc+e of Norway spruce seedlings planted in southern and central Finland between May and July during the warm and dry early summer of 2021. The aim was to clarify i) the survival of seedlings, ii) the possible damage and mortality causing agents (especially drought and pine weevil), and iii) other weather, seedling, site, and work quality factors affecting field performance during exceptional early summer weather conditions, as well as iv) geographical variation in the existence of damage-causing agents. The final aim was also to identify the best practices to ensure good performance in boreal forests in the future climate with exceptional warm and dry weather. We hypothesized that seedling damage would be more serious in the sites with lower precipitation and higher temperatures just before or after planting, the main causes of damage being drought, poor work quality (such as long duration of field storage and late planting dates independent of package method of seedlings, as well as poor quality of planting spot and shallow planting). Certain site factors, such as coarse textures soil, competition of field vegetation and south-west slopes would further increase the damage. One of our hypotheses was also that the seedling size at the time of planting would affect the risk of drought damage: taller seedlings would suffer more than the smaller ones due to the larger transpiring shoots.

2. Material and methods

2.1. Sampling design

The study was undertaken in cooperation with nine companies. Each company randomly selected 7–8 regeneration sites which were representative sites planted with spring planting Norway spruce material. In the case of companies operating throughout Finland, the sites were randomly selected from a smaller operating area. The earliest plantings were done in late April, and the last ones in the middle of July 2021. A total of 65 sites was selected from different parts of southern and central Finland (Fig. 1).

Circular sample plots (28 m^2, radius 3.0 m) were systematically placed on each site. Sampling was based on the area of the regeneration site, which varied between 0.6 ha and 7.0 ha. On smaller sites, eight, and

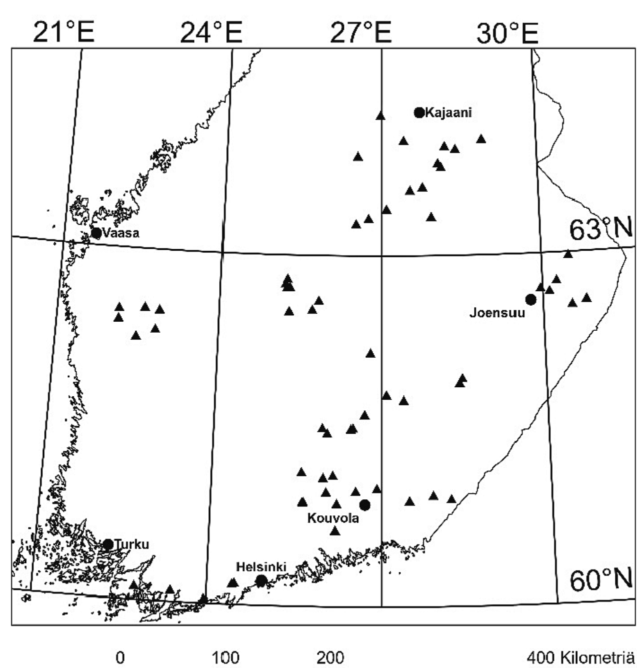

Fig. 1. Location of inventoried regeneration sites in southern and central parts of Finland.

on larger sites, a maximum of 15, sample plots were measured. A total of 2,647 seedlings was measured. The fieldwork was undertaken between 17 September and 13 October 2021. Five people carried out the fieldwork, and they first inventoried a couple of sites together to calibrate their evaluation criteria for subjective variables.

2.2. Measurements

On each sample plot, the MSP method, soil and site type, stoniness, sample plot position, and shading of the nearby forest edge and its tree species were visually determined. MSP methods included spot mounding, inverting, ditch mounding, and other methods (unprepared, scarified patch (organic layer removed), disc trenching). The site type was classified in four categories, based on Tonteri et al. (1990) and Cajander (1949) (very rich, moist (*Oxalis-Maianthemum* type; OMaT); rich, moist (*Oxalis-Myrtillus* type; OMT); medium, sub-mesic (*Myrtillus* type; MT); quite poor, sub-dry (*Vaccinium* type; VT); and for the same fertility levels on peatland sites). Podzol soil texture type was determined to be coarse mineral soil (grain size easy to evaluate with the naked eye), medium-coarse mineral soil (single grains still detectable with the naked eye, grains detached), or fine mineral soil (single soil grains undetectable with the naked eye). The fourth soil type category was peat. Stoniness was classified in three categories by visible stoniness, ranging from few stones (proportion of stones < 30 % in surface soil volume) through normal stoniness (20–60 %), to very stony (>60 %) using the method devised by Viro (1952). The categories for the sample plot position describe whether the plot was on flat terrain or a slope, and the direction of the slope: flat terrain; on top of a hill; at the foot of a hill; on the northern, western, southern, or eastern slope. The nearby forest edge was evaluated to shade (binary variable yes/no) the sample plot if it was on the southern or western side, and its distance was less than twice the height of trees in a stand. Tree species in the shading tree stand was categorized as no shading trees, Scots pine, Norway spruce, broadleaves, or mixed stand.

The type of planting spot for each seedling within a plot was classified as either unprepared soil, humus/peat mound, prepared mineral soil patch, mineral soil mound, or prepared humus/peat patch. The planting spot quality was classified in the following categories: no mound; good-quality mound (covered by mineral soil and only unprepared soil under the mound); logging residues under a mound; a lot of stones in a mound; humus mound. The height of planting spot (HP) was evaluated visually from the unprepared soil surface (5 cm intervals; if a seedling was planted in a patch, the value was negative). The quality of planting was classified as good, planting hole unfilled (open and peat plug was in sight), peat plug above the soil surface, a seedling was planted in the humus although it would have been possible to plant it in mineral soil. Planting depth was visually evaluated as normal (2–4 cm stem below ground), deep (≥5 cm stem below ground), or shallow (<2 cm or peat plug above the soil surface). The microsite shading or warming near a seedling was also evaluated using six categories: no shade; stump; stone; pile of logging residues; another mound or elevated obstacle; bush or tree; another obstacle. Its direction was no shade, north or east, and south or west. The field vegetation (competing water and nutrients with a planted seedling) 1 m radius around a seedling was classified as no vegetation, sparse (only few single herbaceous plants), or rich (thick covering or tall herbaceous or woody plants near a seedling).

From each seedling, the previous-year height and the total height at the time of the measurement were measured with an accuracy of 1 cm from the soil surface to the top of the living part of a seedling. The previous-year height was measured to describe the seedlings size at planting although it describes the height at planting only approximately because some of the seedlings were growing when they were planted. Height growth was calculated as the difference between total and previous-year heights. The existence of lammas growth (yes/no), condition of a seedling [healthy, slightly weakened (some small needle damage that was not predicted to have any effect on the further development of a seedling), weakened (browned or dropped needles, at least a part of stem alive and a seedling was predicted to be survive), dying (seriously damaged, still alive seedling predicted to die), dead], and its leader growth (healthy, multiple leaders, dry or broken shoot), and the reason for damage [drought (dried, brown needles, all or a part of needles dropped off, partly or totally dried shoot), waterlogging (yellowish needles, high water table in the planting spot in spring/autumns), pine weevil (*Hylobius abietis* L.), bark beetle (*Hylastes* spp.), other animals (vole, deer, or other; uplifted seedlings, small browsing damage), frost, planting mistake (planting hole was not filled, a peat plug partly above soil surface), unknown reason] were also determined.

2.3. Seedling material and study sites

The seedling material was grown in small (cell volume 40–80 cm^3; 13 % of inventoried seedlings), medium-sized (80–125 cm^3; 85 %), or large (125–200 cm^3; 2 %; all these seedlings were planted in the very rich or rich sites) peat plugs in Finnish or Swedish nurseries (we had no precise knowledge of which nursery seedlings were supplied to each site). Of the seedlings, 29 % were 1 year old, and the rest were 2 years old; 69 % were grown from seeds collected from Finnish or Swedish seed orchards; and 31 % were grown from seeds collected from normal forest stands. All seedlings were treated against pine weevil before packing and delivery. The seedlings were packed in cardboard boxes (79.5 % of inventoried seedlings) or plastic bags (2 %), or they were stored in open trays (18.5 %). For further analysis, boxes and bags were combined in the box category. Seedlings were winter stored in freezer storage (75 %) or in an open field (25 %). For the further analysis, a new packaging method variable was determined by combining winter storing and packaging type. The categories were open trays (seedlings stored outdoors in winter and packed in open, low sided trays), seedlings that had been packed in closed boxes the previous fall and that were stored in freezer storage during the winter (later called freezer-stored seedlings), and seedlings that were outdoors in the winter and were packed in closed packaging in the spring or early summer (fresh box). The storage duration (timespan between nursery and planting) varied from 0 to 9 weeks for the box-stored seedlings, and from 0 to 2 weeks for the seedlings in open trays. The seedlings in open trays for one site had been transported to the field storage in the previous fall, and the storage duration was 34 weeks (in analysis we use a storage duration of 9 weeks, i.e., the time from snow melt in April to planting for those seedlings).

Clear-cut age was determined to be two years old (14 sites) when the final harvest had been done in the summer of 2019, fall of 2019, or winter of 2020, one year old (11 sites) when the stand had been logged in the summer of 2020, and fresh (38 sites) when harvesting had been done in the fall of 2020 or winter of 2021. For two sites, the clear-cut age was unknown. MSP was undertaken in the same spring or summer on 35 sites, in the previous fall, on 25 sites, in the previous summer, on 4 sites, and one site was unprepared. Most of the seedlings (70 %) were planted in spot mounds, 15 % in inverting, 14 % in ditch mounds, and 1 % in unprepared soil.

Of the seedlings, 29 % were planted in very rich or rich moist site types, 68.5 % in medium or sub-mesic, and 2.5 % in quite poor sub-dry sites. Soil was medium-coarse in 63.5 %, fine in 20 %, coarse in 2 %, and peat in 14.5 % of the planting spots. There were few stones in 36 % and normal stoniness in 61 %, and 3 % of the planting spots were very stony. Fifty-six percent of the seedlings were planted on flat terrain, 7 % on top of a hill, and 10 % at the foot of a hill. The rest were planted on slopes (the percentage in different directions varied between 5 % and 8 %). There was no shade in 70 % of the seedlings.

2.4. Weather data

For each site, weather data were collected from the 1*1 km grid data of the Finnish Meteorological Institute. Using the collected data, we calculated average temperatures (°C), rainfall (mm), sum of global radiation (kJ m^{-2}), and potential evapotranspirations (mm) for one-, two- and three-week periods before and after each planting date, as well as the total precipitation and temperature sum (threshold temperature + 5 °C) on each site, which were used in models.

June and July 2021 were 2–4 °C warmer and precipitation 26–44 mm lower than the long-term average in Finland (Table 1). There were also long periods without any rainfall. On the other hand, temperatures in May and August were close to the average, but precipitation sums higher. September was colder with lower precipitation than the long-term average. The daily potential evaporation (mm) varied between planting periods: it was an average of 53 mm (varying between sites and weeks from 38 to 78 mm) in May, 78 mm (63–89 mm) in early June, 82 mm (78–86 mm) in late June, and 53 mm (67–81 mm) in early July. Daily potential evaporation and air temperature were strongly correlated: the Pearson correlation coefficient was 0.888 ($p < 0.001$) between the two-week daily potential evaporation sum and average daily temperature, for example.

2.5. Statistical analysis

Differences in drought damage or multiple leaders between the packaging methods, planting weeks/periods, or between drought-damaged and healthy seedlings, as well as the prediction models for drought and pine weevil feeding damage were done with a generalized linear mixed model (GLMM) using the PROC GLIMMIX software in SAS for Windows 9.4 (SAS Institute Inc., Cary, NC, USA). When predicting the probability of drought damage, only drought-damaged and healthy seedlings were included, and seedlings damaged by other factors were excluded. This was also the case for the prediction model for pine weevil feeding damage. In the prediction models, we used the same approach as previously used by Luoranen et al. (2018), and model structures are presented there. In the analysis, binary data and the Laplace method were used. In the drought and pine weevil models, assessed weather, site, sample plot, and seedling level variables were tested as predictor factors. The random factors were the regeneration site and sample plot within a regeneration site. The inverse link function was used to transform the linear predictor back to the probabilities. There were three level of variables in the final models: (1) weather variables, clear-cut age, planting period, and packaging method at the regeneration site level; (2) soil and site type, the presence of a shading tree stand and a position on a slope at the sample plot level; and (3) the previous-year height of a seedling, planting place, and its height from a surrounding unprepared soil, planting depth, and mound quality for each seedling. The coefficient of determination (CD) for random effect levels was also calculated as presented by Luoranen et al. (2018).

The differences in the previous-year height, height growth, and total height between the planting periods, packaging methods and drought damage classes (damaged/undamaged seedlings) was analyzed using a linear mixed model (MIXED) in IBM SPSS Statistic, Version 27. The regeneration site and sample plot within a regeneration site were used as random effects. Multiple comparisons were made with the Bonferroni method. The probability level for statistical significance was $p \leq 0.05$ in all analysis.

3. Results

3.1. Quality of work and planting success

The planting point of the seedlings was mineral soil covered mounds for 78 % of seedlings. The rest were planted in mounds made from humus or peat (13 %), patches (either covered by organic material (1 %) or mineral soil (2 %)), or in unprepared soil (6 %). The quality of MSP was good in 90 % of cases, and for the rest, there was no mound (4 %), logging residues or stones were below the mound (5 %), or seedlings were planted in humus (1 %). The medium heights of spot mounds and inverted spots were 5 cm and ditch mounds 10 cm above the surrounding ground level.

The quality of planting was good in 98 % of cases. The planting hole was not filled with soil for 1 % of the seedlings. Most of the seedlings (77.5 %) were planted deeply, the planting depth was determined to be 2–4 cm for 22 %, and 0.5 % were planted at a depth that was too shallow.

On rich (OMT) and very rich sites (OMaT), competing vegetation around a seedling was rich in 11 % and sparse in 10 % of cases. On medium-rich sites (MT), the corresponding values were 3 and 7 %, and on quite poor sites (VT), 1.5 and 1.5 %.

There was an average of 1,648 ± 30 planted seedlings per ha, and there were 1,521 ± 35 living seedlings per ha at the end of the first season (excluding one site on which only spruce seedlings were measured when oak seedlings were also planted). There were already too few seedlings per ha (<1,300; the criteria for complement planting) on 8 % of the sites at the time of the planting, and > 1,500 seedlings per ha on 75 % of sites. The density of living seedlings per ha was > 1,500 (the criteria for good planting success) on 56 % of sites, and < 1,300 (poor success) living seedlings per ha on 22 % of sites at the end of the first season.

3.2. Field performance and damage

Six percent of the seedlings were dead, 2 % dying, 5 % weak, and 19 % slightly damaged at the end of the first growing season. Most (24 %) of the damage and mortality was caused by drought (Fig. 2), no damage was detected on only four sites. Pine weevils damaged an average of 3 % of the seedlings, and their feeding damage was found on 26 sites, and a maximum of 35 % of seedlings within a site were damaged by pine weevils. Pine weevil feeding damage was observed on both the southernmost and northernmost sites near Kajaani without differences between geographical areas. We tried to formulate a prediction model for the pine weevil damage, but no satisfactory model was found. The qualities of mounds and planting spots were always significant

Table 1
Monthly mean temperatures (Tmean, °C), precipitation sums (Prec, mm), number of days with no precipitation (No), and accumulated temperature sums of the growing season 2021 (Tsum, d.d.; threshold temperature + 5 °C) on sites in Joensuu (median Tsum in the data), Sotkamo (minimum), and Kouvola (maximum) from April to September in 2021. In brackets, the 30-year average (1991–2020) monthly mean temperatures and precipitation sums in Joensuu, Kajaani (nearest meteorological station for Sotkamo) and Kouvola based on the statistics of the Finnish Meteorological Institute. Bold values are higher (Tmean) or lower (Prec) than the long-term average.

	Kouvola			Joensuu			Sotkamo		
Month	Tmean	Prec	No	Tmean	Prec	No	Tmean	Prec	No
April	4.0 (3.7)	30 (32)	12	2.4 (2.0)	31 (32)	15	2.1 (1.2)	53 (26)	10
May	10.2 (10.6)	82 (38)	12	9.2 (9.0)	89 (48)	10	8.2 (7.8)	58 (50)	9
June	**19.8 (15.2)**	**35 (64)**	16	**18.6 (14.3)**	**35 (68)**	19	**17.6 (13.4)**	98 (66)	11
July	**21.2 (18.0)**	**35 (66)**	19	**19.8 (17.3)**	**54 (80)**	14	**18.6 (16.2)**	**38 (82)**	14
August	15.0 (16.1)	120 (76)	10	14.4 (15.1)	116 (79)	9	12.9 (14.0)	140 (69)	8
September	8.7 (10.8)	**41 (61)**	17	7.2 (9.8)	**52 (66)**	13	5.9 (8.9)	**40 (60)**	15
Tsum/Prec_sum	1664	416		1440	476		1263	534	

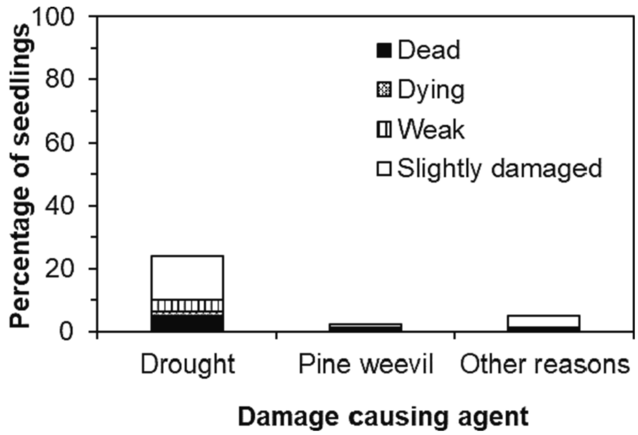

Fig. 2. Proportion of primary damage-causing agents and Norway spruce seedlings' health condition at the end of the first growing season after planting.

predictors (the poor quality of a mound with logging residues or stones under a mound or humus cover, and planting in unprepared soil increased the probability of pine weevil feeding damage), but CDs at regeneration site and sample plot levels were negative (data or model not presented). When only the main cause of damage was determined, and when there was abundant drought damage, it is likely that not all pine weevil feeding damage was assessed, probably explaining the poor model. Some seedlings were also damaged by waterlogging (1 %), *Hylastes* spp. (0.4 %; on 6 sites, a maximum of 9 % of seedlings were damaged within a site), mammals (2 %), or for other reasons (1 %).

The proportion of dead and damaged (unhealthy) seedlings varied between planting weeks ($p = 0.042$; Fig. 3). The differences in the probability of unhealthy seedlings were statistically significant between plantings in July (weeks 28 and 29, three sites) and other weeks. All seedlings planted in July were freezer-stored, packed in closed boxes, and stored from 3 to 9 weeks in the field before planting. On these sites, site preparation had been done at the end of June or on the first days in July. As these procedures are known to be harmful for seedlings (Luoranen et al. 2022a), we excluded four sites planted during weeks 27–29 from further analysis to obtain better models for real drought damage.

Five percent of the seedlings had multiple leaders, and in 3 % of the seedlings, the leader growth was dry. Drought-damaged seedlings had more abnormal leaders than healthy seedlings ($p < 0.001$ for Drought

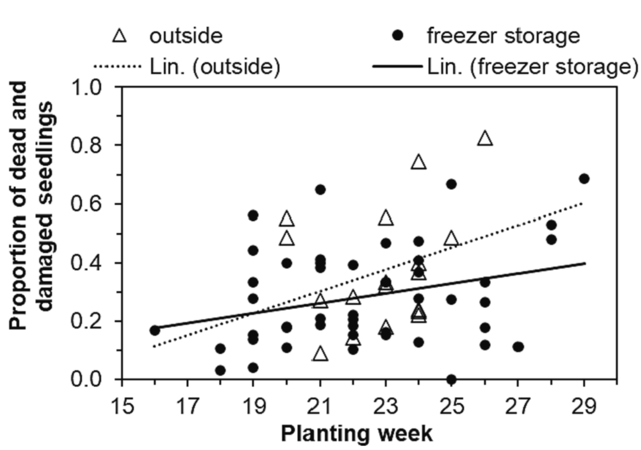

Fig. 3. Proportion of dead and damaged Norway spruce seedlings planted between the last week of April (week 16) and the middle of July (week 29). Seedlings were stored either outside or in freezer storage during winter and spring before planting. Each symbol indicates the proportion of unhealthy seedlings on a regeneration site and the trendlines indicate the linear trend in the proportion of damages for seedlings stored outside or in a freezer storage.

(D)), especially in fresh seedlings packed in boxes (predicted probability 0.28), but also in seedlings in open trays (0.11) and to some extent in freezer-stored seedlings (0.04; p = for Packaging method M and D × M; no differences in planting periods and therefore excluded from the model).

3.3. *Prediction model for drought damage*

In the first run, planting week and packaging method and their interaction, as well as several weather factors and their interaction with the site, sample plot, and seedling level factors, were significant. The model explained 89 and 60 % of variation on the regeneration site and sample plot level respectively. However, it was difficult to interpret the model results, and standard errors of estimates for continuous variables in the model were infinite. We thus combined planting weeks to three planting periods: May (weeks 16–21, including the last week in April), early June (22–24) and late June (25–26, including the first week in July); and dropped some weather factors from the model. With the final model we avoided overestimation, but still found the most important variables estimating the probability of drought damage of newly planted seedlings. The final model explained 73 % of regeneration site variation and 33 % of sample plot variation.

In the final model, the continuous predicted fixed factors were the height of a planting spot (HP), the precipitation sum a week before planting (BPrep1) and their interaction, the previous year's shoot height, and the average air temperature during the two weeks after planting (ATemp2), and the class factors were the planting period and packaging method and their interaction, and the packaging method interaction with HP, the shading tree stand and its interaction with ATemp2, the mound quality, the soil texture type and its interaction with BPrec1, the site type, the position of a sample plot on a slope and the planting depth (Table 2). In the final model, there were quite many explanatory factors and the number of cases in some categories was small causing some uncertainty in the results. However, the explanatory factors in the model were logical and likely describe the effects of these factors in right scale as compared with each other.

In the May and early June plantings, no statistically significant differences between packaging methods were found, but in late June, freezer-stored seedlings had a lower risk of drought damage than fresh seedlings in boxes or open trays (Fig. 4e). An increase in the height of the previous-year shoot aboveground level also increased the risk of drought damage in freshly packed seedlings in boxes compared to freezer-stored seedlings (Tables 2, 3; Fig. 5a).

From other factors, the risk of drought damaged increased most when the seedlings were planted in poor quality mounds (logging residues or stones in a mound or seedlings were planted in humus; Fig. 4c) and they were planted shallow (Fig. 4d). Site fertility clearly increased drought damage in quite poor sites and slightly in very rich and rich sites as compared to the medium rich sites (Fig. 4a). The effect of soil texture type depended on the BPrec1. In medium-coarse soils, the increased BPrec1 only slightly reduced the risk of drought damage, but the predicted probability of drought damage was>0.5 in coarse soils, when there was no rain in the previous week, but the risk reduced quickly when BPrec1 increased (Table 2; Fig. 5b). In peat, the probability of drought damage varied from 0.16 to 0.20. In fine-textured soils, increased BPrec1 increased the risk of drought damage, especially in May plantings. Although statistically significant, the effects of the position of a sample plot on a slope (Fig, 4b), the shading tree stand and its interaction with ATemp2 (Fig. 5c), as well as the interaction of the height of a planting spot and the BPrec1 (Fig. 5d) on the risk of drought damage were minimal.

3.4. *Seedling growth*

The previous-year shoot was taller in seedlings that had suffered from drought when the seedlings were in open trays before late-June

Table 2
Estimates, standard errors (SE), the number of observations in each category (N), the significances of parameters of fixed effects, and the variances of random effects (regeneration site and sample plot within a regeneration site) in a generalized linear mixed model for the drought damage of newly planted Norway spruce seedlings. In the final model, reference categories and the number of observations in each reference category (brackets) for different fixed effects were as follows: Shading tree stand 'No shade' (N = 1,549); Mound quality 'Good' (N = 2,068); Packaging method (M) 'Open tray' (N = 414); Planting period (P) 'May' (N = 950); M × P 'Freezer-stored seedlings in boxes in May' (N = 809), 'Fresh seedlings packed in boxes in May' (N = 76), 'Open trays in May' (N = 65), 'Open trays in early June' (N = 301), 'Open trays in late June or early July (N = 48); Soil texture type 'Medium-coarse' (N = 1,435); Site type 'Medium rich, MT' (N = 1,507); Position of a sample plot ' Flat terrain or at the foot of a hill' (N = 1,531); Planting depth 'Deep' (N = 1,723). BPrec1 is precipitation sum a week before planting (mm); ATemp2 is the average air temperature two weeks after planting (°C). The CD is the coefficient of determination in different random effects. In the modelling, damage other than that caused by drought were excluded.

Effect type		*N*	*Estimate*	*SE*	*DF*	*t-value*	*p-value*
Intercept			−3.571	1.06	49	−3.37	0.002
Previous-year height (H0)			0.058	0.03	1,712	1.99	0.047
Height of a planting spot (HP)			−0.004	0.01	1,712	−0.27	0.785
BPrec1			−0.009	0.01	1,712	−0.88	0.381
HP × BPrec1			0.002	0.001	1,712	2.7	0.007
ATemp2			0.094	0.06	1,712	1.45	0.148
Shading tree stand (S)	Shade	702	−2.062	0.74	1,712	−2.8	0.005
ATemp2 × S	Shade		0.094	0.04	1,712	2.35	0.019
Mound quality	No mound	80	−0.267	0.40	1,712	−0.66	0.507
	On the logging residues or humus mound	103	1.063	0.28	1,712	3.85	<0.001
Packaging method (M)	Freezer-stored box (B)	1630	0.391	0.85	1,712	0.46	0.647
	Fresh box (FB)	207	−1.245	1.17	1,712	−1.07	0.286
Planting period (P)	Early June (EJ)	973	−1.000	0.84	1,712	−1.19	0.234
	Late June–early July (LJ)	328	1.684	1.21	1,712	1.39	0.166
M × P	B–EJ	579	0.468	0.71	1,712	0.66	0.509
	B–LJ	242	−2.866	1.06	1,712	−2.71	0.007
	FB–EJ	93	1.566	0.99	1,712	1.58	0.115
	FB–LJ	38	−1.519	1.30	1,712	−1.17	0.241
M × H0	B		−0.036	0.03	1,712	−1.11	0.269
	FB		0.057	0.04	1,712	1.35	0.179
Soil texture type (ST)	Fine	446	−0.697	0.37	1,712	−1.87	0.061
	Coarse	46	1.978	0.81	1,712	2.43	0.015
	Peat	324	0.366	0.36	1,712	1.02	0.307
BPrec1 × ST	Fine		0.034	0.01	1,712	2.39	0.017
	Coarse		−0.167	0.07	1,712	−2.35	0.019
	Peat		−0.091	0.02	1,712	−4.12	<0.001
Site type	Quite poor (VT)	67	1.029	0.45	1,712	2.26	0.024
	Very rich (OMaT) or rich (OMT)	677	0.504	0.21	1,712	2.4	0.017
Position	On top of a hill or on a slope	720	0.353	0.17	1,712	2.04	0.042
Planting depth	Normal	513	−0.361	0.17	1,712	−2.14	0.032
	Shallow	15	1.473	0.68	1,712	2.16	0.031
Variances of random effects			*Estimate*	*SE*			*CD*
Regeneration site			0.344	0.125			0.73
Sample plot within a site			0.284	0.130			0.33

plantings, or when the fresh seedlings had been packed in closed packaging and planted in May or late June, compared with healthy seedlings in the same planting periods (Table 4, Fig. 6a). In the freezer-stored seedlings planted in July, the drought-damaged seedlings were slightly taller than the healthy seedlings. The height growth of drought-damaged seedlings was lower in all packaging methods and planting periods (Table 4, Fig. 6b), indicating that drought-damaged seedlings were also shorter at the end of the first fall (Table 4, data not shown). Lammas growth was found in 6 % of the seedlings.

4. Discussion

4.1. Planting success

The average mortality of the seedlings, six percent, after the first growing season was higher than was observed in previous studies (1–3 %) in central and southern Finland (Luoranen and Viiri 2012; Luoranen et al. 2022). The weather conditions during the following winter and spring, such as long snowless periods with very low temperatures in midwinter or low precipitation in the spring and early summer, can worsen the previous year's seedling damage (Luoranen et al. 2018). It is therefore probable that some of the weakened seedlings observed in our study may die during the following winter, and mortality levels may increase later. In the study of Luoranen et al. (2018a), 6–14 % of fall-planted Norway spruce seedlings, and on average, 10 % of seedlings planted in the previous year (Luoranen et al. 2022) died during severe winter conditions. In the studies of Luoranen et al. (2018, 2022), seedling damage was assessed in the early summer of the second season after planting. We performed the inventory at the end of the first season to better distinguish the damage caused by summer drought from winter damage.

Overall, the planting success was rather good (number of living seedlings per ha > 1500) on about half of the inventoried sites, and poor (<1,300) on every fifth site. In the study of Pikkarainen et al. (2020), the planting success of Norway spruce seedlings was good on 84 % of planting sites in central and southern Finland after the first winter. In the study of Luoranen and Viiri (2021), there were>1,500 seedlings per ha in 44 % of peatland and 79 % of mineral soil sites three years after planting. Compared to those results, an exceptionally dry and warm summer significantly reduced the planting success. However, it should be noted that the planting densities were lower than the recommended densities for Norway spruce seedlings (1,800 seedlings per ha; Metsänhoidon suositukset, Tapio 2022). When the probability of severe weather conditions increases in the warming climate (Ruosteenoja et al. 2018), the risk of damage caused by abiotic stresses like early summer drought also increases (Venäläinen et al. 2020). Our results showed that there were several ways to reduce the risk of drought through operational choices and good-quality work, but it is impossible to completely avoid it. To ensure full-density young forests with high carbon sequestration capacity in the future climate, planting density should therefore

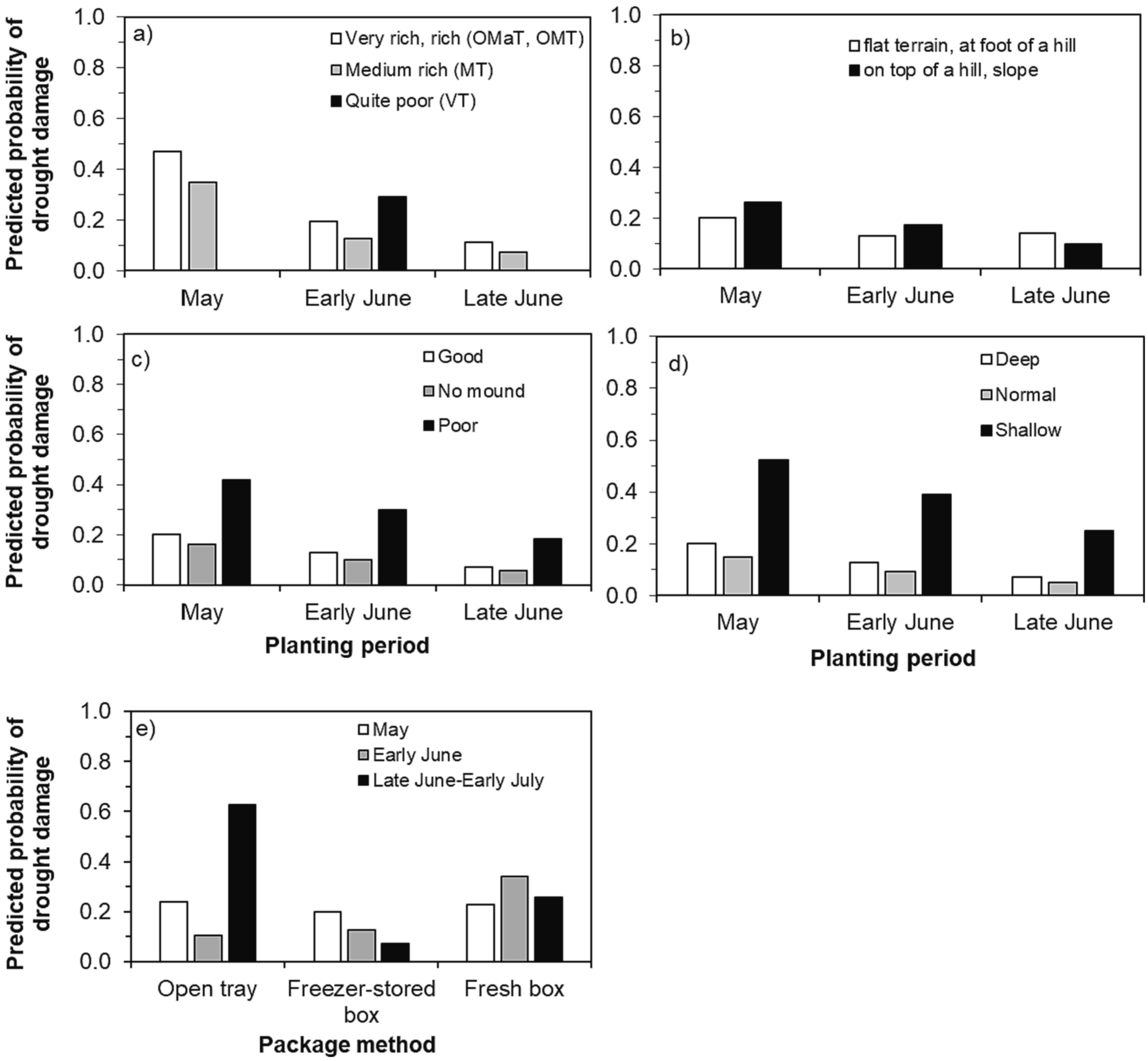

Fig. 4. Predicted probability of drought damage of newly planted Norway spruce seedlings that had been planted a) on different site types, b) in different positions on a slope, c) in mounds of different quality, or d) to different planting depths (deep > 5 cm, normal 2–4 cm, shallow, peat plug surface in sight) in different planting periods, and e) in different planting periods when open stored seedlings had been packed in open trays, or closed boxes (fresh box) or freezer-stored seedlings had been packed in boxes. Bars in a–d) are only presented for freezer-stored seedlings packed in boxes. In all figures, other parameters in the drought damage model were in the reference category (see Table 2), or continuous variables were in the average value.

be sufficient and close to the recommended one.

In our study, seedling age at planting, container size type, or differences between seedlings grown from seeds collected from a stand or seed orchard (genetically improved seeds) had no effects on drought damage. Previously, Chen and Nelson (2020) observed no differences in the first- and second-year mortality of planted interior Douglas fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) and western larch (*Larix occidentalis* Nutt.) seedlings between seedlots or genetic improvement in a temperate region in Idaho, USA. Saksa (2011) observed no effect of seedling age on the mortality of Norway spruce seedlings in central Finland. On the other hand, in the study of Johansson et al. (2015), Norway spruce seedlings grown in the smallest container types (smallest cell volume) had the highest mortality-three years after planting.

4.2. Weather conditions

There was a very long drought with a low precipitation sum and high air temperatures in June and July 2021 in all the inventoried areas, although there were some differences in precipitation and air temperatures between the sites. These differences explained some of the probability of drought damage. Both predicting factors in the model are partly linked to the planting date: the precipitation sums were higher, and temperatures lower, in May than in June and July. This explains why fewer seedlings were damaged by drought in May than in other periods. In June and July, drought damage was more probable on sites with lower precipitation sums and higher temperatures, although other factors such as the growing phase of seedlings affected damage levels more than the weather.

Previously, Helenius et al. (2002) observed that if soil was moist at planting, well-watered seedlings could survive a 3-week drought. Well-watered seedlings could even survive planting in dry soils, but if the peat plugs were already dry at planting, the risk of damage and mortality was high (Helenius et al. 2005a). In our study, the drought was even longer than three weeks on many sites. It was therefore unsurprising that drought damage was found on most of them. It is possible to reduce this risk with pre-planting watering.

Table 3
Type III test of fixed effects in generalized linear mixed model for the drought damage of newly planted Norway spruce seedlings presented in Table 2.

Effect	Num DF	Den DF	F Value	Pr > F
Previous-year height	1	1,712	18.40	<0.001
Height of a planting place (HP)	1	1,712	0.07	0.785
PPrec1	1	1,712	9.93	0.001
ATemp2	1	1,712	5.09	0.024
Shading stand (S)	1	1,712	7.86	0.005
ATemp2 × S	1	1,712	5.54	0.019
Mound quality	2	1,712	7.78	<0.001
Packaging method (M)	2	1,712	0.84	0.430
Planting period (P)	2	1,712	0.98	0.376
M × P	4	1,712	3.94	0.003
H0 × M	2	1,712	3.93	0.020
Soil texture type (ST)	3	1,712	3.81	0.010
BPrec1 × ST	3	1,712	9.72	<0.001
Site type	2	1,712	5.16	0.006
Position	1	1,712	4.16	0.042
Planting depth	2	1,712	4.95	0.007
BPrec1 × HP	1	1,712	7.29	0.007

4.3. Planting periods and growing phase of seedlings

In the freezer-stored seedlings, mortality and damage levels were high on the three latest planting dates in July. In these cases, the planting of seedlings was delayed, and storage durations were lengthened by at least three weeks, due to the wait for site preparation. Hänninen et al. (2009) and Luoranen et al. (2022a) have clearly shown that the risk of damage other than drought increases if freezer-stored seedlings are planted in July. For these freezer-stored seedlings, the growing season is too short for growth and hardening processes to be completed before the first fall and winter frosts (Hänninen et al. 2009). In addition, during the summer months, the storage duration of seedlings in closed packaging cannot exceed 1–2 days (Luoranen et al. 2019). This is the case even with freezer-stored seedlings if they are thawed, and air temperatures are high (Helenius et al. 2004). Previously, Nilsson and Örlander (1995) and Luoranen et al. (2005; 2022a) also observed increased mortality in seedling material intended for spring plantings and planted late (July).

In the other planting periods, the risk of drought damage to the freezer-stored seedlings was affected by factors other than the planting period. In the open trays and fresh seedlings packed in boxes, the risk of drought increased the later in June they were planted. The probability of drought damage was influenced by the growing phase of the seedlings, i.e., whether the seedlings were dormant or growing at the time of planting. Seedlings planted in May were still dormant or were just flushing. Freezer-stored seedlings were more or less dormant at the time of planting in all planting periods. The effect of the growing phase of seedlings was partly linked to the seedlings' height at planting. In our study, the increasing previous-year height increased the risk of drought damage more in seedlings delivered in open trays or fresh seedlings in boxes than in the freezer-stored seedlings. Seedlings in open trays and fresh seedlings in boxes had flushed, and the current-year growth was probably longer the later the seedlings were planted (see, e.g., Luoranen et al. 2005). A greater transpiring needle area in tall seedlings than in shorter ones causes greater water demand and increases the risk of drought damage (Grossnickle 2012, and reference therein). The effect of increasing seedling height on drought stress and mortality has also been found in interior Douglas fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) and western larch (*Larix occidentalis* Nutt.) seedlings (Chen and Nelson 2020). Very short young seedlings, grown in a small cell volume,

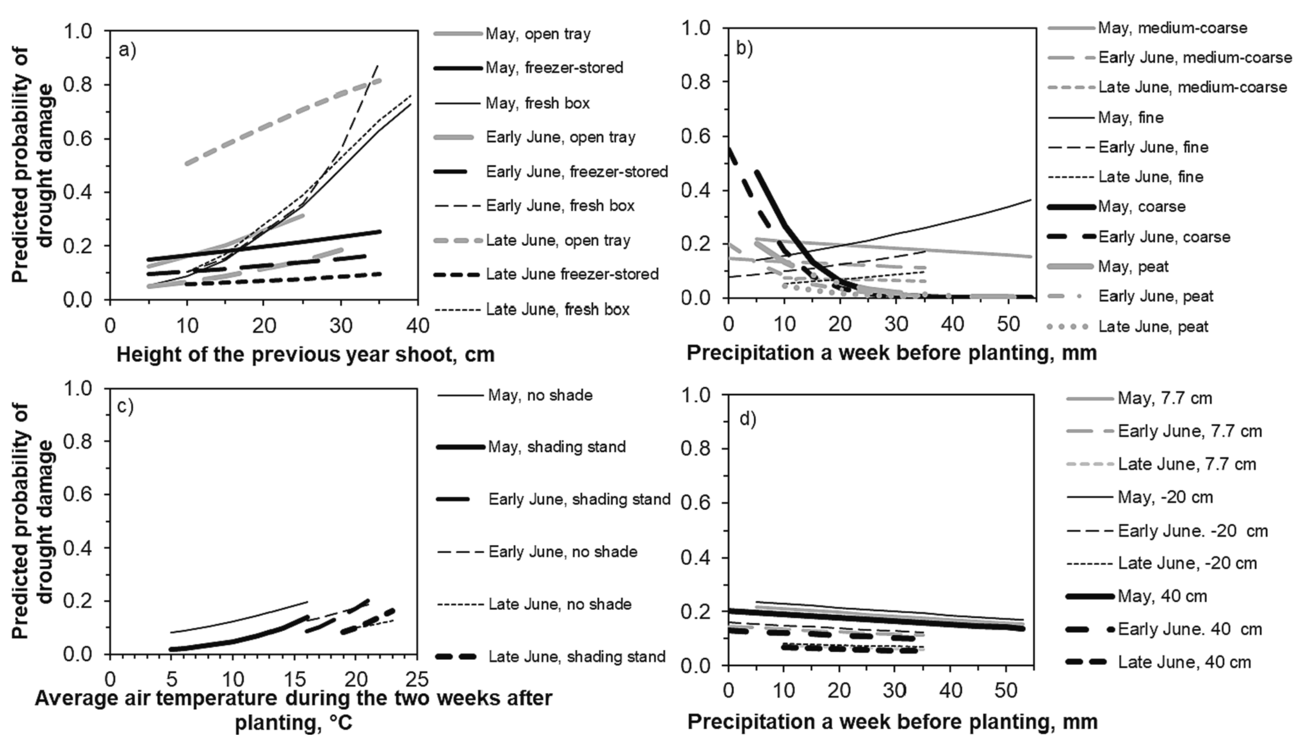

Fig. 5. Probabilities of drought damage of newly planted Norway spruce seedlings in different packaging method (open tray, freezer-stored seedlings, fresh seedlings packed in closed packaging) and planting period (May, early June, late June–early July) combinations, a) with a varying height of the previous year's shoot, b) in different soil texture types (fine, medium-coarse, coarse, peat) and planting period combinations with a varying precipitation sum a week before planting, c) in differing shade from a nearby tree stand (no shade, shading stand) and planting period combinations with varying average air temperature two weeks after planting, and d) at different planting spot heights (observed minimum, average, and maximum heights) and different planting period combinations with a varying precipitation sum a week before planting. In b–d), curves are presented only for freezer-stored seedlings. In all figures, model parameters other than the presented ones were in the reference category (see Table 2), or continuous factors were at their average value (for the previous-year height average, the values of each packaging method were used). In all figures, only the observed ranges of continuous variables are presented.

Table 4
Statistical significances of mixed model analysis for the height of previous-year shoots (H0), the seedling height at the end of the first growing season (H1), and the first-year height growth.

Source	H0		H1		Height growth	
	F	Sig.	F	Sig.	F	Sig.
Intercept	659.18	<0.001	928.45	<0.001	256.53	<0.001
Planting period (P)	0.055	0.983	0.290	0.832	0.472	0.703
Packaging method (M)	1.786	0.177	0.273	0.762	3.476	0.038
Drought (D)	7.944	0.005	47.75	<0.001	205.21	<0.001
P × M	0.127	0.972	0.251	0.908	0.921	0.458
P × D	2.526	0.056	2.062	0.103	2.519	0.056
M × D	3.400	0.034	0.416	0.660	5.142	0.006
P × M × D	2.227	0.064	0.595	0.666	1.297	0.269

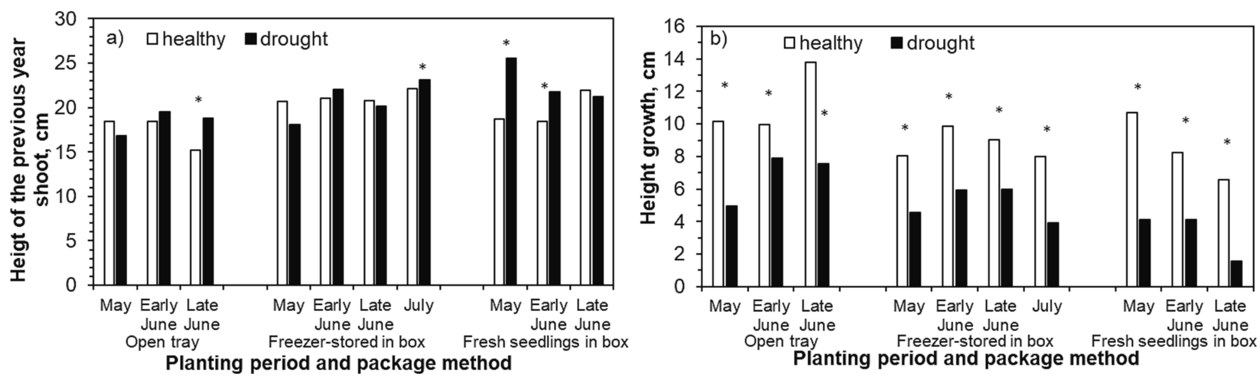

Fig. 6. a) height of the previous year's shoot and b) height growth during the first growing season of healthy and drought-damaged seedlings, which had been planted in May (including the last week in April), early June, late June (including first week of July), and which were packed in open trays or in closed boxes either in the previous fall (freezer storage) or in the same spring (fresh). Asterisks indicate the statistically significant differences between healthy and drought-damaged seedlings within each packaging method and planting period combination.

are also very vulnerable to drought (Johansson et al. 2007), but such seedlings were not included in our experiment. In addition to seedling height, stem diameter also plays an important role in the seedlings' performance potential. Slim, tall seedlings have an increased mortality risk (Grossnickle 2005; Chen and Nelson 2020). In our inventory study conducted at the end of the first growing season, it was impossible to determine the seedlings' initial diameter.

Previously, Helenius et al. (2005b) observed that dormant Norway spruce seedlings sustained the four-week post-planting drought period better, and their root growth reduced less than seedlings planted at the growing stage. Helenius et al. (2005b) also measured seedlings' xylem water potential, observing that dormant seedlings were capable of restoring water at night when growing seedlings failed to rehydrate, followed by reduced photosynthesis after a three-week drought. Growing seedlings have succulent new needles with incomplete cuticular development, which increases stomatal and cuticular transpiration, resulting in an ineffective control of water loss than in dormant seedlings (Grossnickle 2000). Spruce seedlings in the growing phase are therefore the most susceptible to drought (Grossnickle 2000).

In the study of Helenius et al. (2005b), chlorophyll fluorescence measurements (F_v/F_m) showed that after a four-week drought, the photosynthetic apparatus of growing seedlings was damaged, whereas in dormant seedlings, no changes in F_v/F_m were observed. Luoranen et al. (2019) observed that F_v/F_m was reduced after 3–7 days when nondormant Norway spruce seedlings were kept in closed packaging in the middle of May or August. The photosynthetic apparatus of flushed, fresh seedlings packed in closed packaging in the early summer can be damaged in drought stress even more quickly than seedlings delivered in open trays. This may explain why the freezer-stored seedlings in our experiment had less drought damage than other types of seedlings, and why fresh seedlings packed in boxes had more drought damage in early June than other seedlings. In a warming climate with an increased probability of early summer droughts, the planting of freezer-stored seedlings might be the safest option if the freezer storage ends in the middle of June (Hänninen et al. 2009), and the seedlings are planted at the end of June.

Drought-damaged seedlings grew less than the healthy seedlings. Reduced height growth of drought-stressed seedlings is also observed in previous studies (e.g., Roberts and Cannon 1992; Helenius et al. 2005b). The reduced growth was partly caused by dry leader shoots, but it can also be caused by reduced photosynthesis (Helenius et al. 2005b) and/or earlier growth cessation (Matisons et al. 2021). Hájíčková et al. (2021) studied the resistance of four-year-old Norway spruce seedlings to drought stress during flushing. They observed that the shoot growth reduced more under severe drought stress, whereas moderate stress affected root growth more. In our study, the drought damage classification was based on visual symptoms, meaning that they had already suffered severe damage. The effect of drought may continue in the following season, because the second-year growth of drought-stressed seedlings has also been found to be reduced (Turtola et al. 2003).

4.4. Site conditions

Although there were only a few observations on coarse and poor sites, the higher probability of drought damage on those sites was obvious. In coarse textured soil, the pore size between soil particles is high, and water holding capacity is low (Grossnickle 2000). In the study of Matisons et al. (2021), soil water potential in sandy soil dropped quickly without irrigation, when the reduction in silty sand and peat was slower. In their study, water potential in peat remained quite high with some irrigation. Therefore, in our study, even the small amount of precipitation after planting probably increased soil moisture in peat, helping seedlings avoid drought stress.

In fine soils, increasing pre-planting precipitation increased the predicted probability of drought damage, especially in May plantings. A possible explanation is that high precipitation caused waterlogging first and then a lack of oxygen in the rooting zone, and this had weakened the seedlings. Waterlogging also slows root growth (Grossnickle 1987; Repo et al. 2017). Later during a drought in the warm periods in June and July, those poorly rooted and weakened seedlings may have been at higher risk of drought damage. In the fine textured soils, ditch mounding was used more often as an MSP method than in the other soil texture types, and those sites were also more fertile. Ditch mounds were higher than in the other planting spots. The effect of drought in fine soil may therefore be caused by factors other than soil texture, such as soil fertility or the height of the planting spot.

The risk of drought damage increased on more fertile sites compared to the medium rich sites. On fertile sites, there was also more competing vegetation around the seedlings. Vegetation competition has been shown to increase soil moisture stress and the drought damage of newly planted seedlings (Nilsson and Örlander 1995; Pinto et al. 2012). In our study, the existence of vegetation around a seedling or the age of a clear-cut did not directly affect the drought risk. However, Nilsson and Örlander (1995) observed that mortality caused by drought was higher in older clear-cuts than in fresh ones, and that the amount of competing vegetation increased in those older clear-cuts.

A shading tree stand near the sample plot slightly reduced the drought damage, but only when the seedlings were planted in May, and air temperatures were<20 °C during the two weeks after planting. At higher air temperatures, no such effects were found. Evaporation was high at high temperatures, because there were high correlations between the average air temperature two weeks after planting and the daily potential evaporation. In these conditions, newly planted seedlings consume water so much that the shading of the nearby forest does not affect the drought risk. At lower temperatures, the evaporation and transpiration of the seedlings are lower, and shading can reduce it to some extent. The shading of a nearby tree stand can also affect biomass allocation. Schall et al. (2012) observed that decreasing light availability increased the aboveground biomass of Norway spruce seedlings and reduced the percentage of fine roots. In June and July plantings, shading may therefore have increased the imbalance between shoots and roots, reducing the positive effects of shading on transpiration.

On slopes, the risk of drought damage was slightly higher than on flat terrain or at the foot of a hill, without a difference in the direction of a slope. On slopes, the water flows downwards, and it is obvious that the risk of drought increases. There can be differences between the aspects of slopes—for example, respiration can be higher on south-facing slopes than north-facing ones (Griffiths et al. 2009). In very hot and dry conditions, temperatures and radiation are also high on flatter terrain, explaining why the risk levels between different sample plot positions were small. We found no effect of microsite shading on drought damage in Norway spruce seedlings. The responses to microsite shading may be species-specific: Reely and Nelson (2021) observed that the presence of microsite shading increased the survival of western larch and grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) seedlings but not Douglas fir seedlings in Idaho, USA.

4.5. *Quality of site preparation and planting*

In poor quality mounds and in shallow planting, the risk of drought damage increased. The logging residues and upturned humus in mounds reduced the capillary rise of water to the root zone, and their loose structure increased the risk of poor root-soil contact. To ensure continuous water availability to planted seedlings, root plugs must be at least partly in the upturned humus layer (Örlander 1986) with good root-soil contact (Grossnickle 2000). During dry periods, the top mineral layer of mounds dry (Örlander 1986), and when only root plugs of shallow planted seedlings are in the top mineral soil layer, the risk of drought damage increases, as our and previous results have shown (Örlander 1986; Luoranen and Viiri 2016). Similarly, a slight increase of damage risk with the increasing height of the planting spot (the high probability that roots of planted seedlings were in the upper mineral soil) is caused by the drying of the upper layer of mounds and lack of water. In the study of Heiskanen et al. (2013), the highest ditch mounds were driest in a dry summer. The importance of mounds covered with mineral soil with only upturned humus under it (without logging residues or stones) in preventing abiotic damage in planted seedlings has also been observed in previous inventory studies by Luoranen et al. (2018, 2022a).

4.6. *Pine weevil feeding damage*

One of our aims was to examine the geographical variation of damage-causing agents. In addition to drought, the pine weevil feeding damage was the only one that had enough observations for this evaluation. In Långström's old study (1982), the abundance of pine weevil decreased from south to north in Finland. In our study, no differences between geographical areas were found from the south coast to the Kainuu region in the northern part of central Finland. On average, the probability of pine weevil feeding damage was 3 %, but there was a high level of damage on some sites. In the study of Luoranen et al. (2022), 6–10 % of seedlings protected chemically or physically against pine weevil and planted in mounds died because of the damage caused by pine weevils in southeast Finland until the end of the second season. However, in the study of Heiskanen et al. (2013), <1 % of chemically protected and mound-planted seedlings died in central Finland. Water stress in seedlings has been shown to increase seedlings' risk of pine weevil feeding (Selander and Immonen 1992). In our study, only the main cause of damage was assessed, meaning that no other damage-causing agents were determined if there was drought damage. In contrast, if the main cause of the damage was determined to be pine weevil feeding, minor drought damage was not taken into account. The probabilities of both total drought and pine weevil feeding damage may thus have been underestimated. However, drought stress also affects the concentrations of defense compounds such as terpens, which may affect seedlings' resistance to herbivores like pine weevil in the following years (Turtola et al. 2003).

The good quality of mounds was also essential in preventing pine weevil feeding damage, as has been shown in several previous studies (e.g., Petersson et al. 2005; Wallertz et al. 2018; Luoranen et al. 2017). Our results confirm the well-known fact that planting in unprepared soil significantly increases the risk of pine weevil feeding (e.g., Petersson and Örlander 2003; Luoranen et al. 2022b).

5. Conclusions

During dry and warm weather in the early summer, the risk of drought damage to newly planted Norway spruce seedlings was real, causing seedling mortality. However, most of the damage was slight, causing needle and leader growth damage, as well as reduced height growth. An increasing precipitation sum before planting explained the differences in drought damage between the sites to some extent, although there was otherwise no geographical variation either in drought or pine weevil feeding damage. An increasing air temperature after planting increased the risk of drought damage, but it was partly caused by differences in the planting dates: in May, the risk of damage was smaller than on the later dates. It is possible to reduce the risk of both drought and pine weevil feeding damage by planting seedlings sufficiently deep in mineral-soil-covered mounds, under which there is only a layer of humus. The risk of drought damage can be reduced by avoiding planting Norway spruce seedlings on easily drying sites with coarse textured soil. On rich sites with dense vegetation cover surrounding planted seedlings, the risk of drought increased. On those sites, quick planting after the clear-cut is important. Based on this study, in a warming climate with early summer drought periods, freezer-stored seedlings are a safer choice for plantings in June than seedlings that have overwintered outdoors and flushed before planting. Avoiding planting seedlings that are too tall reduces the drought damage risk in severe weather conditions. In practical operational work, it is important to try to adjust the quantities and schedules of site preparation and planting so that the field storage duration of seedlings is as short as possible. Of course, this can be difficult when, for example, the number of seedlings and deliveries must already be planned in the previous year when the progress of spring weather conditions is unknown. In conclusion, it is impossible to completely prevent drought damage in newly planted Norway spruce seedlings, but by optimizing operational choices and measures like the choices of combinations of planting dates, packaging methods and planting densities the development of full-density, fast-growing young Norway spruce forests with a good carbon sequestration capacity can also be ensured in a warming climate. In future studies, the damage risks of the newly planted seedlings of other tree species suitable for boreal Nordic forests should be investigated as a comparison with Norway spruce.

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The study was undertaken in cooperation with UPM, Stora Enso, MellanåPlant, Södra Skogsreviret, and the Forest Management Associations of Etelä-Savo, Lakeus, Keski-Suomi, Päijät-Häme, Pohjois-Karjala, and Savotta. The cooperating companies identified the regeneration site and background data. However, the cooperating companies played no role in the study design, analysis, or data interpretation, in the writing of the report, or in the decision to submit the article for publication.

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CRediT authorship contribution statement

Jaana Luoranen: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Johanna Riikonen:** Conceptualization, Methodology, Writing – review & editing. **Timo Saksa:** Conceptualization, Investigation, Methodology, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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